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NONDESTRUCTIVE HEAT-TREATMENT REGIMES FOR GLASS AND CERAMIC PLATES

A. F. Kovalenko[1]

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Unilateral heating of a glass or ceramic plate freely fixed along its contour by a surface source is considered in the context of a quasistatic non-coupled problem. An analytical relationship is obtained, which is a criterion of thermal strength of the plate and allows for identifying nondestructive treatment regimes. It is shown that for many materials there is a range of Fourier number variations in which the plate under treatment can be destroyed by thermoelastic stresses.

Methods for treating optical glasses and ceramics, along with traditional high-temperature annealing, include surface treatment by continuous radiation of a CO_2 laser [1 – 4]. One-sided heating of a plate may create conditions under which thermoelastic stresses may become critical in the technological process. To identify nondestructive treatment regimes, we will consider solving a non-coupled quasistatic problem of thermal elasticity for a plate freely fixed along its contour.

Let us accept that the flux density is uniformly distributed across the laser beam section and constant in time. The absorption index of the plate material is sufficiently high and laser radiation absorption can be taken as surface. This condition is well satisfied under the effect of radiation of a continuous CO_2 laser on optical and quartz glasses; its penetration depth is about 20 μm [4]. Under the effect of one-sided laser radiation the temperature field inside the plate will vary only across the plate thickness and can be calculated from the equation presented in [5], assuming that there is no radiation loss on the surface $\xi = 1/2$ experiencing the radiation effect:

$$T(\xi, \tau) = T_0 + \frac{qh}{\lambda}\left\{\tau + \frac{12\xi^2 + 12\xi - 1}{24} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\cos\left[\frac{n\pi}{2}(2\xi + 1)\right]e^{-n^2\pi^2\tau}\right\}, \quad (1)$$

where $T(\xi, \tau)$ is the temperature; $\xi = z/h$ is the dimensionless coordinate; z is the coordinate varying from $h/2$ to $-h/2$; h is the plate thickness; $\tau = \alpha t/h^2$ is the Fourier number; α is the thermal conductivity of the plate material; t is the duration of the effect; T_0 is the initial temperature; q is the laser radiation flux density absorbed by the plate surface; $q = q_0(1 - R)$; q_0 is the flux density of laser radiation falling on the plate surface; R is the reflection coefficient.

Under the effect of a temperature field, thermoelastic stresses arise in the plate freely fixed along its contour [5]:

$$\sigma_x(\xi, \tau) = \sigma_y(\xi, \tau) = \frac{E\alpha_T\, qh}{(1 - \nu)\lambda}\left\{\frac{12\xi^2 + 12\xi - 1}{24} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\cos\left[\frac{n\pi}{2}(2\xi + 1)\right]e^{-n^2\pi^2\tau}\right\}, \quad (2)$$

where α_T is the average TCLE of the plate material within the temperature interval; E is the Young modulus; ν is the Poisson coefficient.

Analysis of relationship (2) indicates that thermoelastic stresses vary across the plats thickness from the maximum compressive stresses in the plate section ($\xi = 1/2$), where the temperature is maximal, to maximum tensile stresses in the plate section ($\xi = -1/2$), where the temperature has the minimal value.

Since optimal materials have tensile strength approximately 5 times lower than compressive strength [6], we will perform a subsequent analysis for tensile stresses. We obtain the relationship for maximum tensile stress from Eq. (2):

$$\sigma_x^{\max}(\tau) = \sigma_y^{\max}(\tau) = \frac{E\alpha_T\, qh}{(1 - \nu)\lambda}\left[\frac{1}{6} + \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\, e^{-n^2\pi^2\tau}\right]. \quad (3)$$

[1] Peter the Great Military Academy of Strategic Missile Forces, Moscow, Russia.

Based on expression (3), we find the flux density of laser radiation causing destruction of the plate by means of thermoelastic stresses:

$$q_T = \frac{\sigma_t(1-\nu)\lambda}{E\alpha_T h\left[\frac{1}{6} + \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}e^{-n^2\pi^2\tau}\right]}, \tag{4}$$

where σ_t is the tensile strength of the material.

Using Eq. (1), we determine the laser radiation flux density required to reach the temperature of phase transition on the surface of the plate under radiation:

$$q_f = \frac{(T_f - T_0)\lambda}{h\left(\tau + \frac{1}{3} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{e^{-n^2\pi^2\tau}}{n^2}\right)}, \tag{5}$$

where T_f is the phase transition temperature.

By dividing Eq. (4) by expression (5) and specifying condition $q_T/q_f \geq 1$ (q_f is the flux density under the phase transition), we obtain, after mathematical transformations,

$$\frac{\sigma_t(1-\nu)}{E\alpha_T(T_f - T_0)} \geq \frac{\frac{1}{6} + \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}e^{-n^2\pi^2\tau}}{\tau + \frac{1}{3} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}n^{-2}e^{-n^2\pi^2\tau}}. \tag{6}$$

Thus, an analytical relationship is derived, which is a criterion of thermal strength of a plate freely fixed along its contour experiencing one-sided heating from a surface source.

Let us analyze relationship (6). The left part of the inequality is a constant characterizing the ratio of the tensile strength of material of the plate freely fixed along its contour to the maximum tensile stress in this plate under one-sided surface heating.

The right part of the inequality is a function of the dimensionless parameter $f(\tau)$, i.e., the Fourier number. Figure 1 presents a graphic solution of inequality (6) for optical glasses K8 and LK3. The left part of the inequality does not depend on τ and is represented on the plot by straight lines parallel to the abscissa axis. The function $f(\tau)$ does not depend on the properties of material. This function in Fig. 1 is represented in the form of a curve with a maximum value at $\tau \approx 0.2$ equal to 0.275.

If inequality (6) is satisfied, the temperature of the irradiated plate surface reaches the phase transition level under a lower flux density than the level required for destruction of the plate by thermoelastic stress. For instance, for optical glass K8 [7] the left part of the inequality is equal to 0.07 and it is satisfied at $\tau \leq 0.006$ and $\tau \geq 2.2$. The treatment regime at $\tau \geq 2.2$. is not effective with respect to energy since it leads

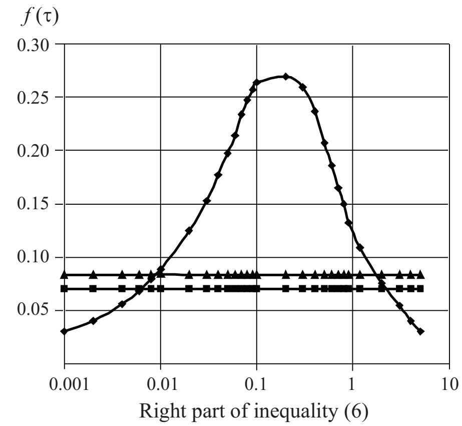

Fig. 1. Graphic solution of inequality (6): ♦) Fourier number $f(\tau)$; ■) glass K8; ▲) glass LK3.

to heating of the whole plate. In the parameter interval of $0.006 < \tau < 2.2$ inequality (6) is not satisfied; consequently, destruction of the plate by thermoelastic stresses will occur under a lower flux density level than that required to reach the surface temperature of phase transition. For quartz glasses KI, KV, and KU [8] the left part of the inequality is equal to 0.83 and the interval of destruction of the plate by thermoelastic stresses does not exist. Below we list the properties of some optical materials, whose source data are taken from [7 – 10].

Materials	**Properties of materials according to the left part of inequality (6)**
Optical glass:	
LK3	0.084
K8	0.070
TF1	0.065
TK12	0.063
Quartz glasses	0.830
Ceramics:	
KO3	0.065
KO4	0.012
KO6	1.130

Is can be seen from the above data that a range of thermoelastic destruction under one-sided heating with a surface heating source exists for materials considered (except for optical ceramic KO6 and quartz glasses).

Thus, inequality (6) is a criterion of thermal strength of a plate freely fixed along its contour under one-sided heating with a surface source and makes it possible to identify nondestructive regimes for laser treatment of optical and ceramic material surfaces.

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